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Donlagic et al.

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(45) **Date of Patent: Sep. 22, 2015**

(54) **OPTICAL FIBER SENSORS HAVING LONG ACTIVE LENGTHS, SYSTEMS, AND METHODS**

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(65) **Prior Publication Data**

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Related U.S. Application Data

(62) Division of application No. 13/046,648, filed on Mar. 11, 2011, now Pat. No. 8,655,117.

(51) **Int. Cl.**

G02B 6/00	(2006.01)
C03B 37/14	(2006.01)
G01B 11/16	(2006.01)
G01D 5/26	(2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***C03B 37/14*** (2013.01); ***G01B 11/18*** (2013.01); ***G01D 5/268*** (2013.01); ***G01L 1/242*** (2013.01); ***G01L 11/025*** (2013.01); *G01B 2290/25* (2013.01)

(58) **Field of Classification Search**

CPC C03B 37/14; G01L 11/025; G01L 1/242; G01D 5/268; G01B 11/18

USPC 385/12, 31, 39

See application file for complete search history.

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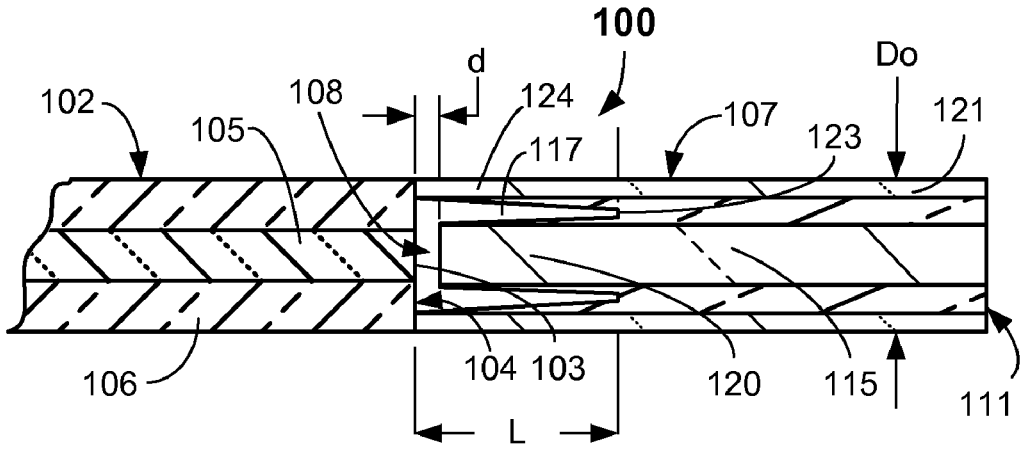
Primary Examiner — Ryan Lepisto

(74) *Attorney, Agent, or Firm* — Dugan & Dugan, PC

(57) **ABSTRACT**

Optical fiber sensors adapted to measure strain or pressure are disclosed. The optical fiber sensor has a lead-in optical fiber having an end surface at a forward end, and a first optical element having a body with an outer dimension, Do, a front end surface coupled to the lead-in optical fiber, a pedestal including a retracted surface that is spaced from the front end surface, the retracted surface at least partially defining an optical cavity, a gutter surrounding the pedestal, the gutter having a gutter depth defining an active region of length, L, the first optical element further exhibiting L/Do≥0.5. Also provided are systems including the optical fiber sensor, and methods for manufacturing and using the optical fiber sensor. Numerous other aspects are provided.

19 Claims, 10 Drawing Sheets



(51) **Int. Cl.**
G01L 11/02 (2006.01)
G01L 1/24 (2006.01)

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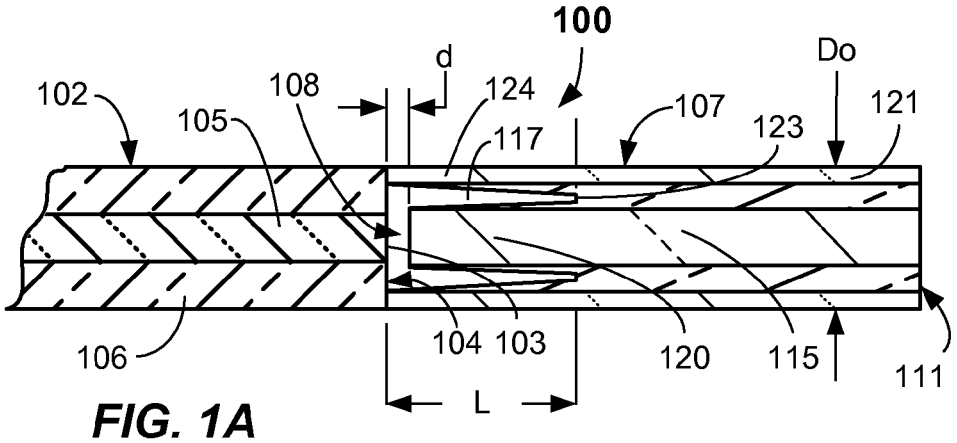


FIG. 1A

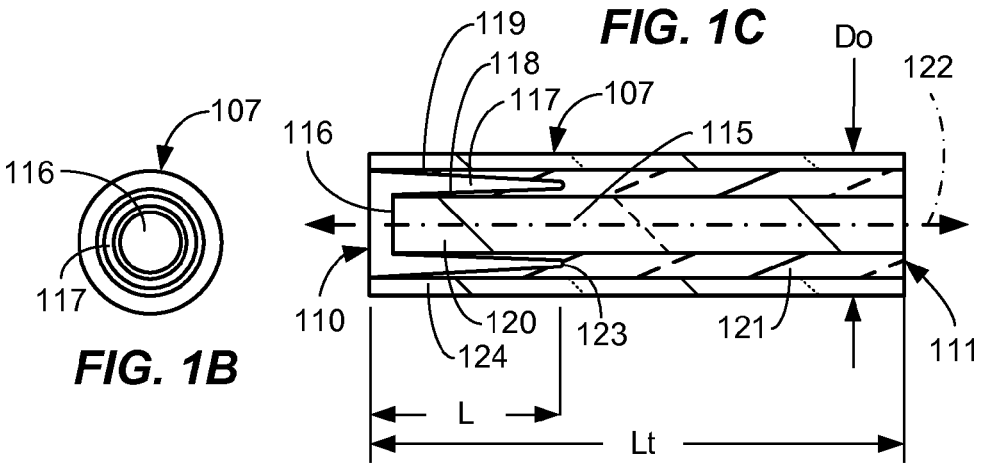


FIG. 1C

FIG. 1B

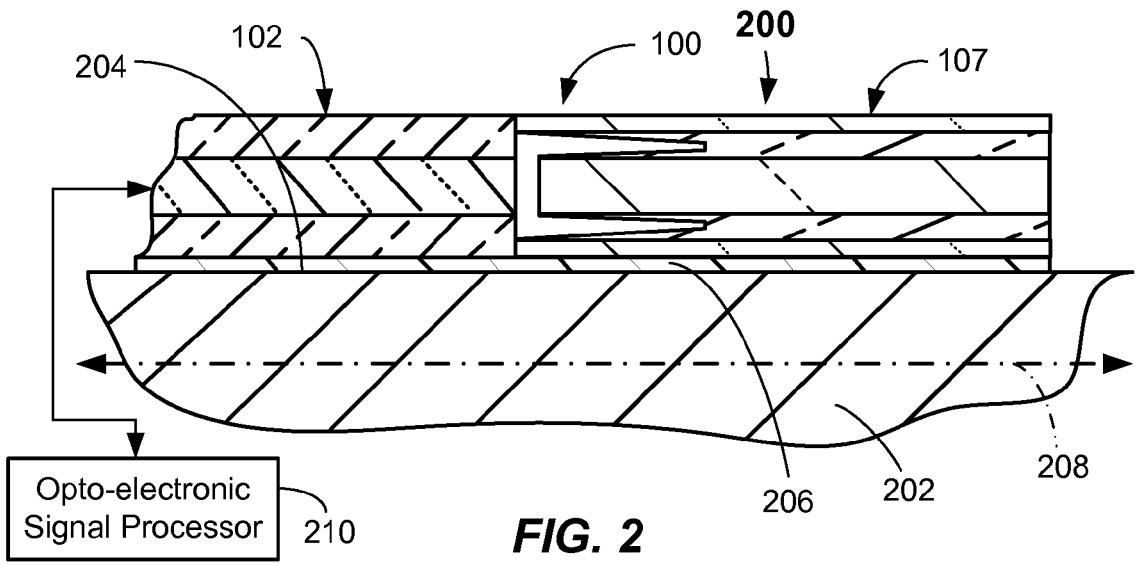
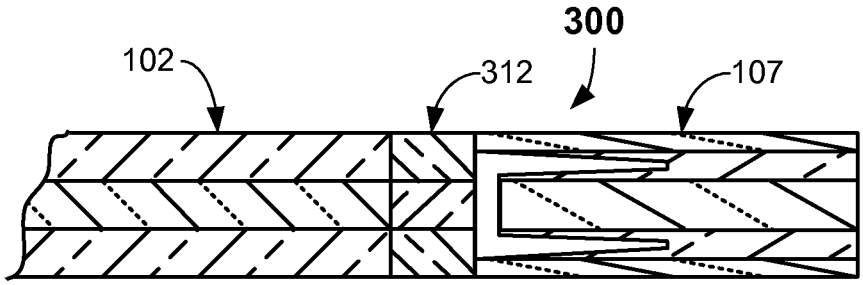


FIG. 2



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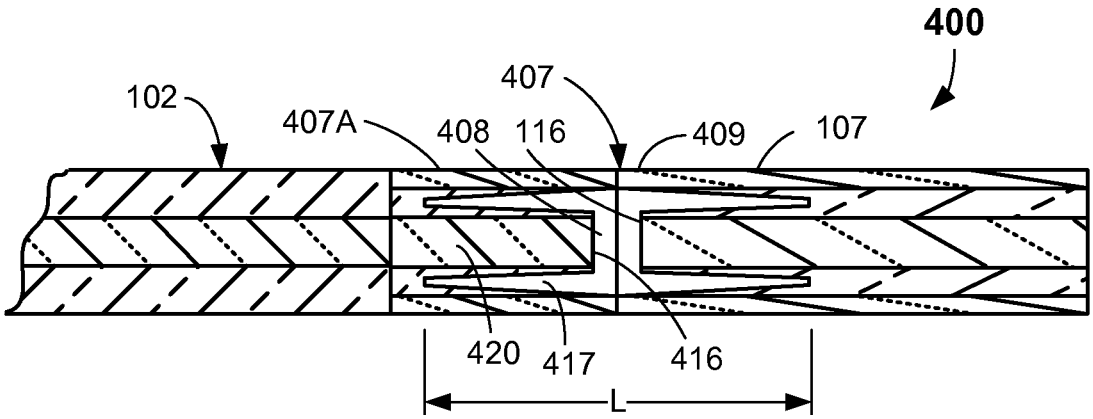

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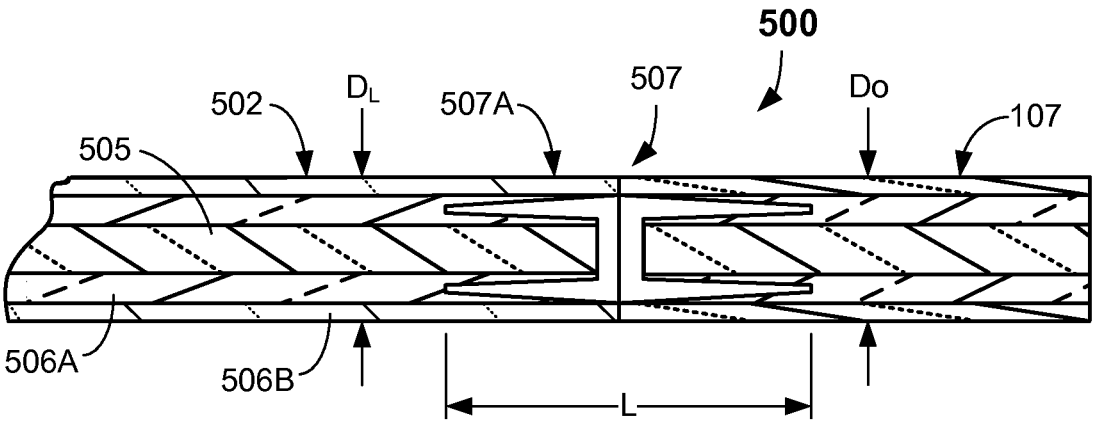

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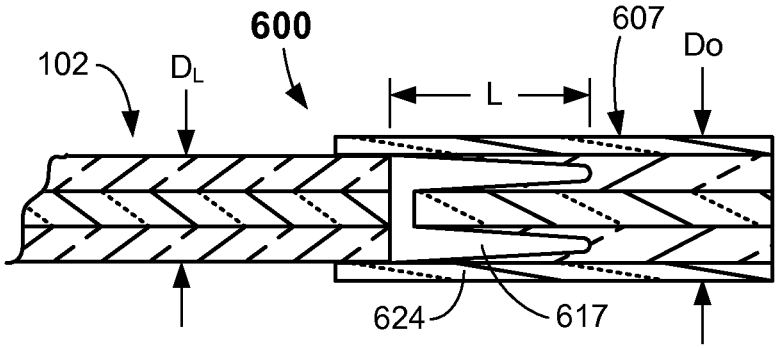


FIG. 6

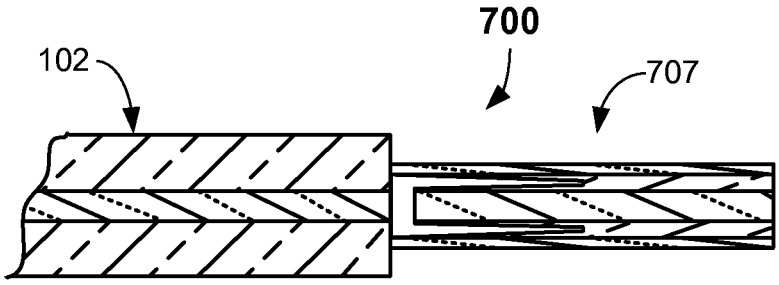


FIG. 7

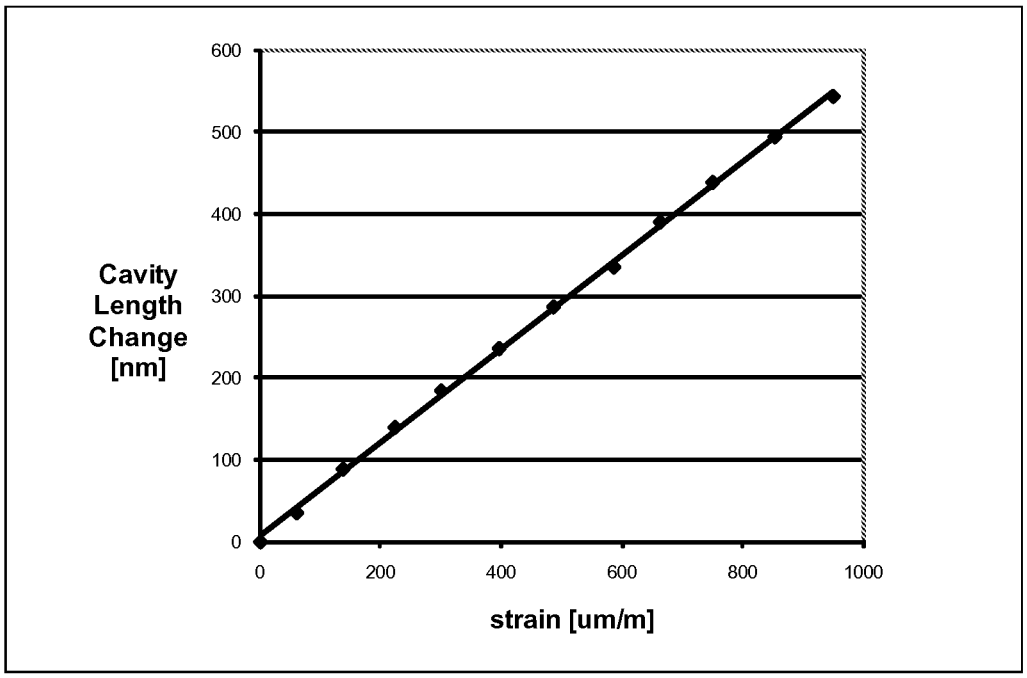

Cavity Length Change [nm]
600
500
400
300
200
100
0
0
200
400
600
800
1000
strain [um/m]

FIG. 8A

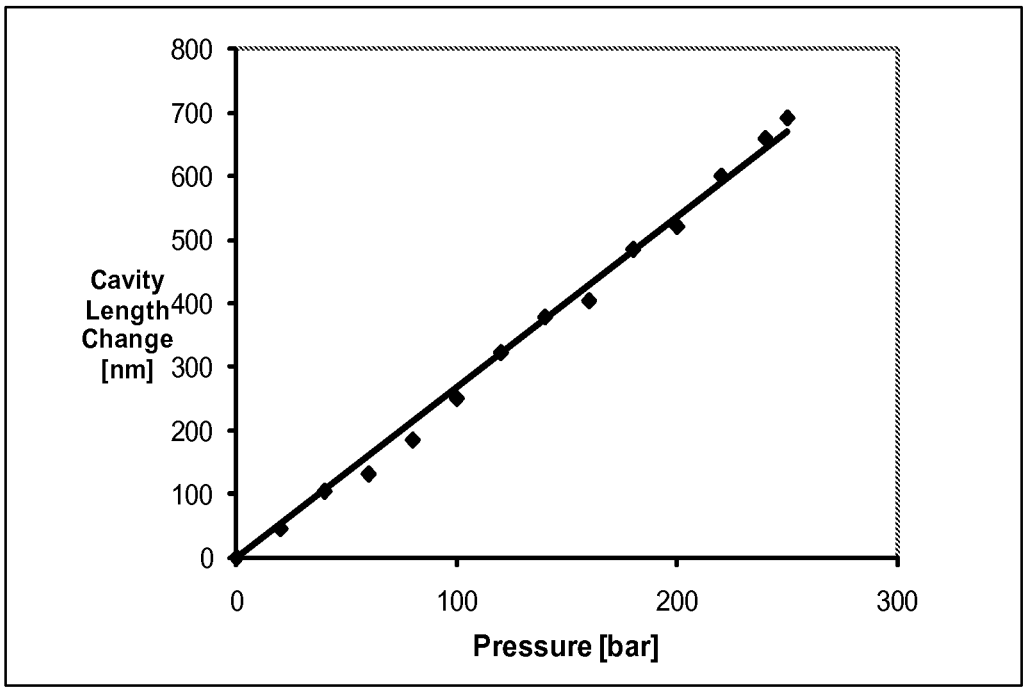

Cavity Length Change [nm]
800
700
600
500
400
300
200
100
0
0
100
200
300
Pressure [bar]

FIG. 8B

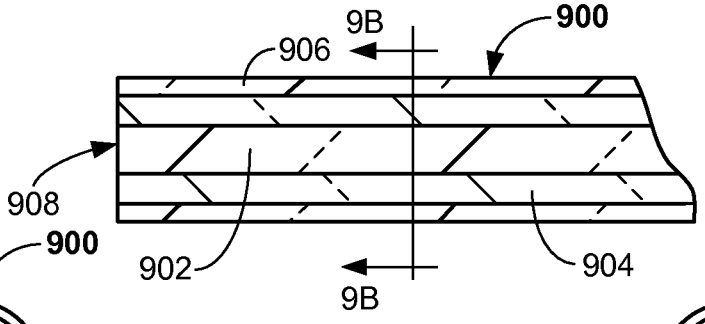


FIG. 9A

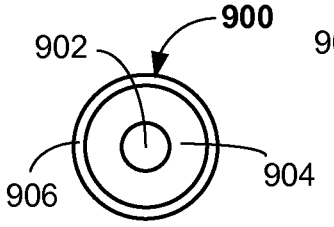


FIG. 9B

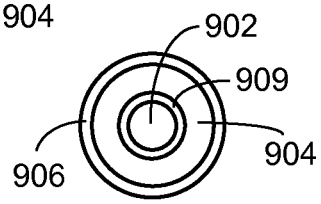
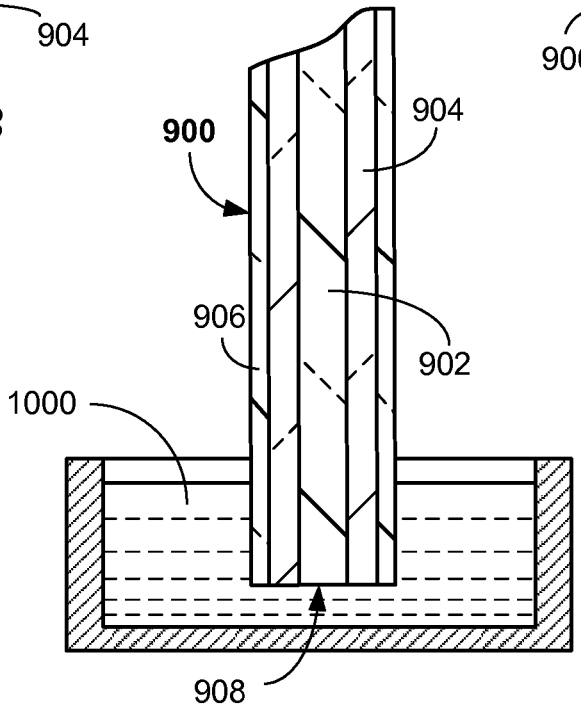


FIG. 9C



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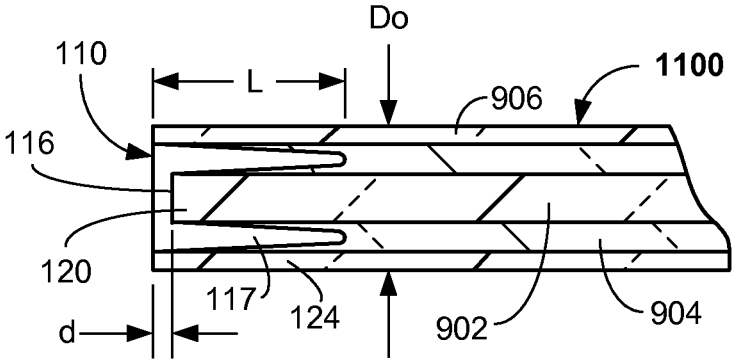

FIG. 11

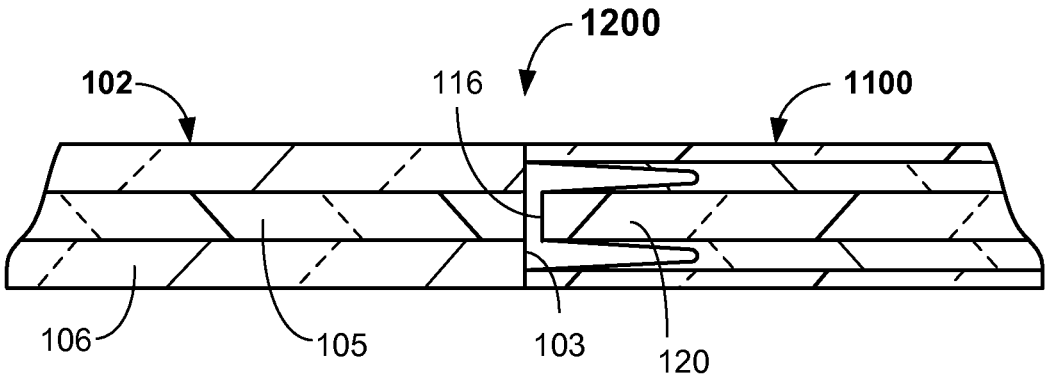

FIG. 12

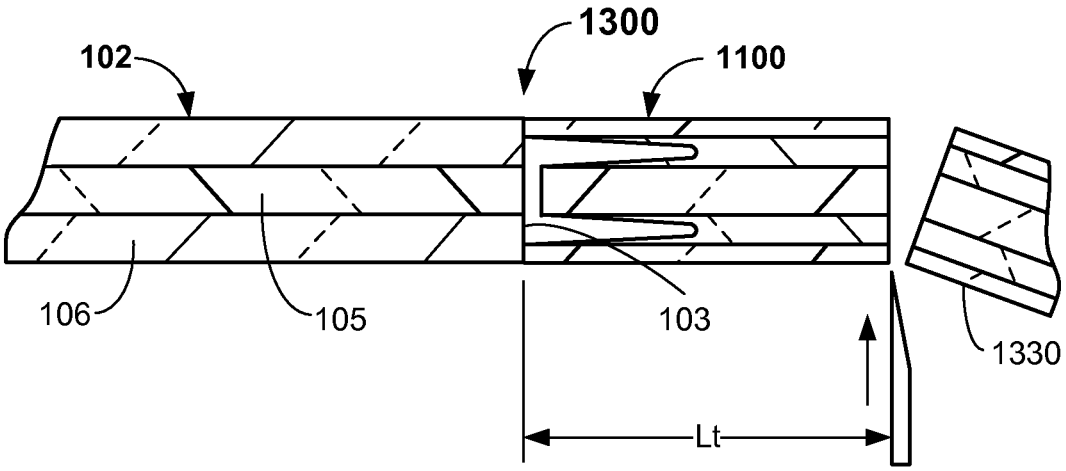

FIG. 13

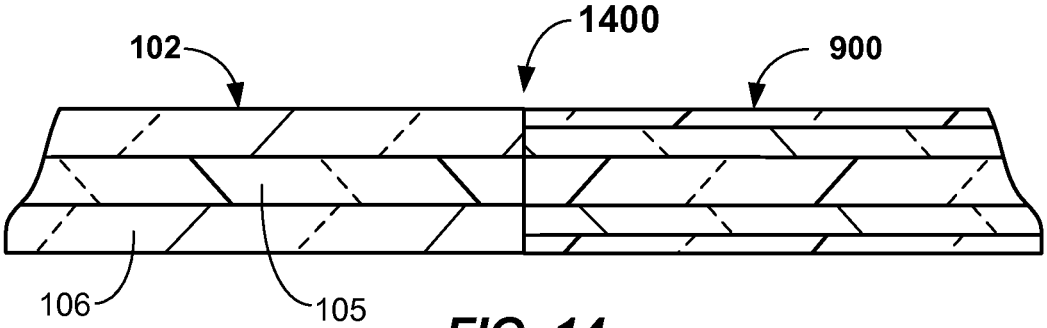

FIG. 14

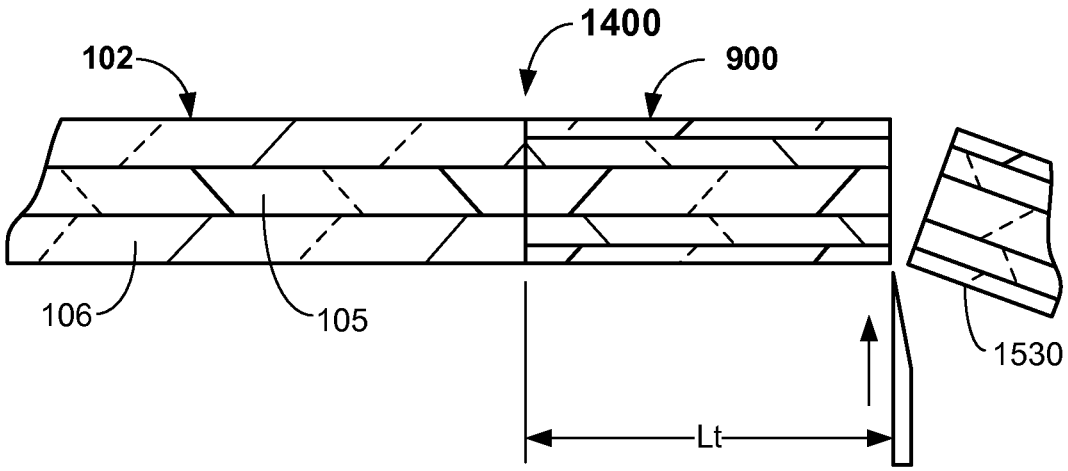

FIG. 15

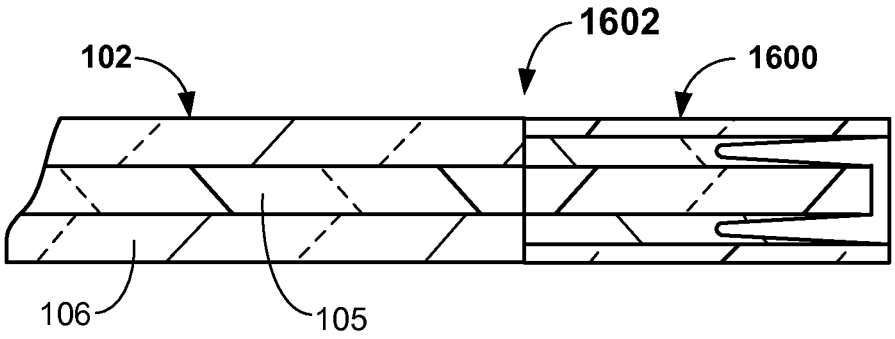

FIG. 16

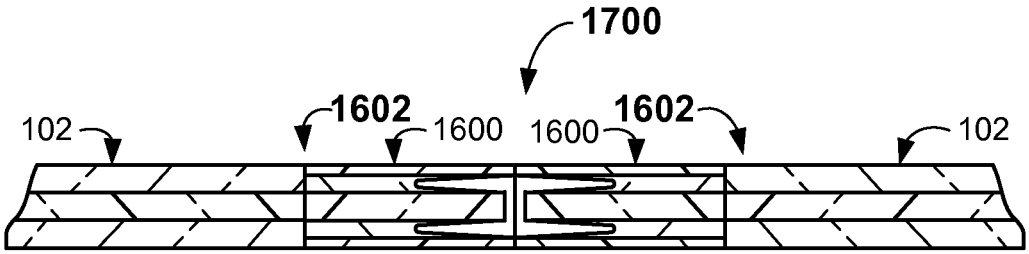

FIG. 17

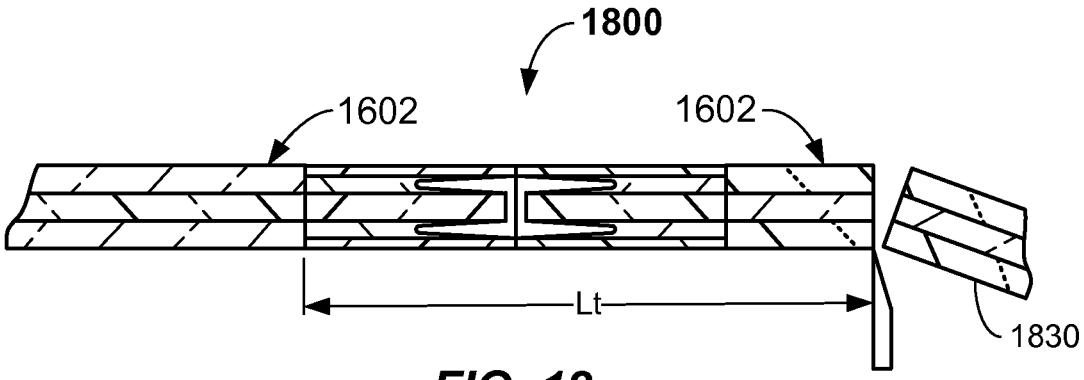
1800
1602
1602
Lt
1830

FIG. 18

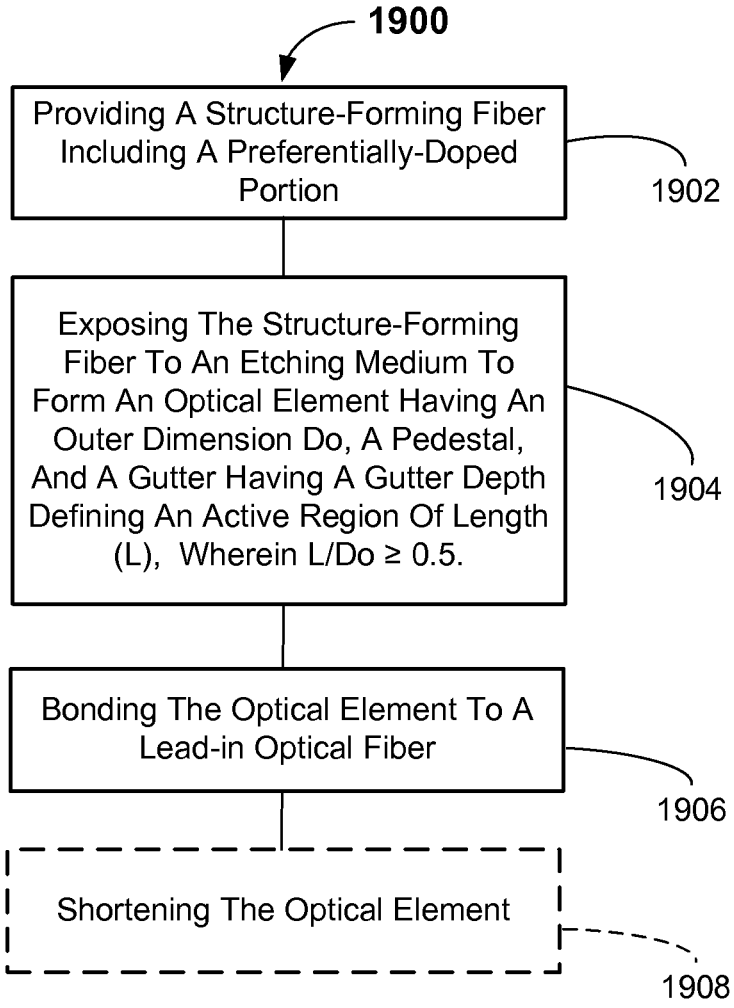
1900
Providing A Structure-Forming Fiber Including A Preferentially-Doped Portion
1902
Exposing The Structure-Forming Fiber To An Etching Medium To Form An Optical Element Having An Outer Dimension Do, A Pedestal, And A Gutter Having A Gutter Depth Defining An Active Region Of Length (L), Wherein L/Do ≥ 0.5.
1904
Bonding The Optical Element To A Lead-in Optical Fiber
1906
Shortening The Optical Element
1908

FIG. 19

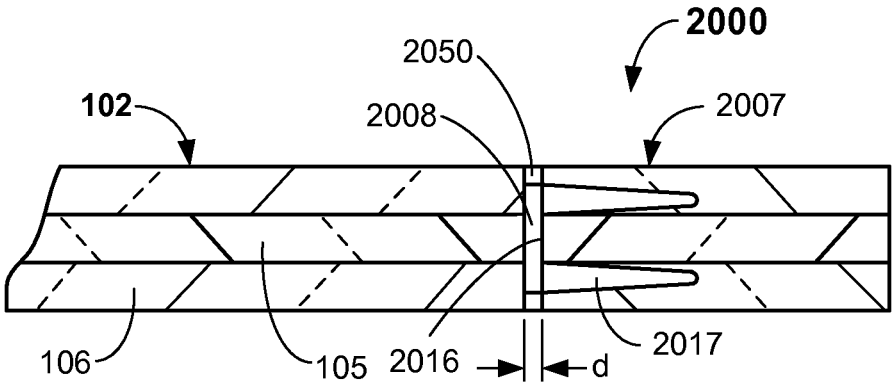
2000
2050
102
2008
2007
106
105
2016
d
2017

FIG. 20

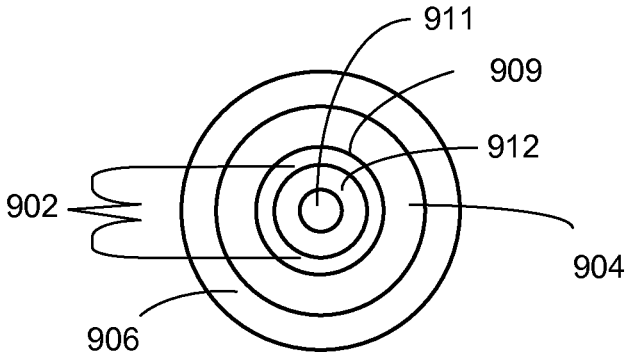
911
909
912
902
904
906

FIG. 21

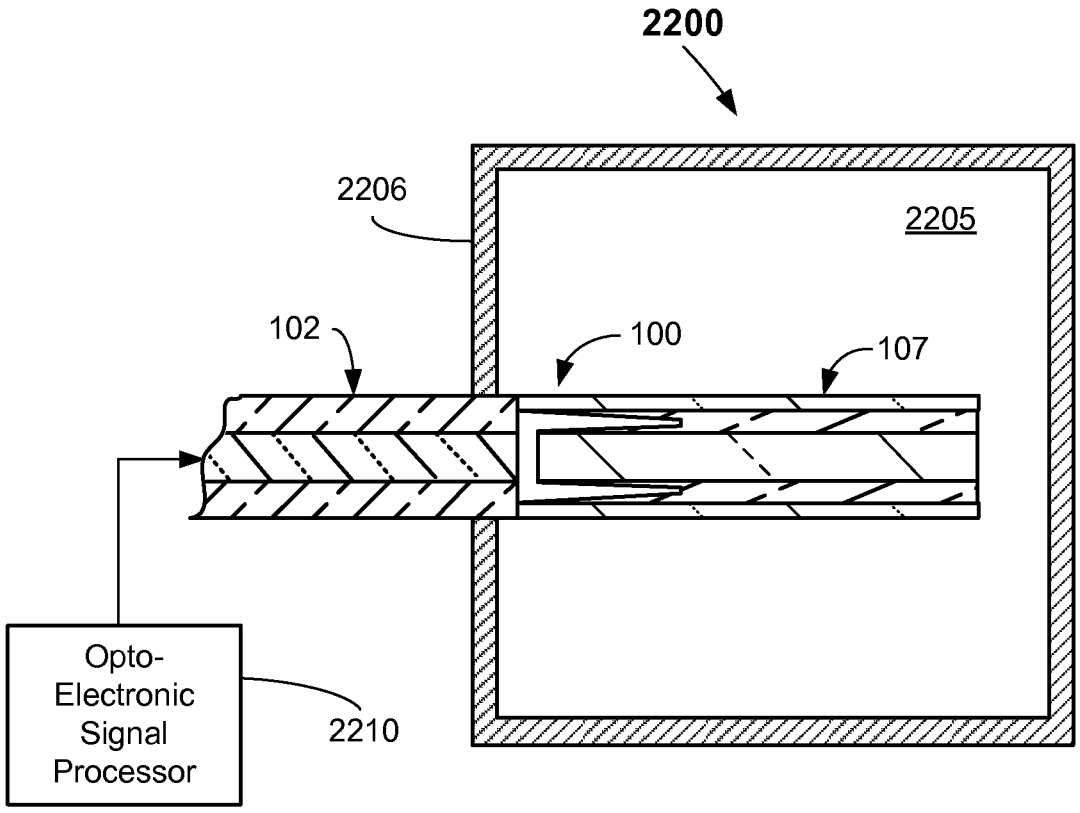
2200
2206
2205
102
100
107
Opto-
Electronic
Signal
Processor
2210

FIG. 22

OPTICAL FIBER SENSORS HAVING LONG ACTIVE LENGTHS, SYSTEMS, AND METHODS

RELATED APPLICATIONS

This application is a divisional of and claims priority to U.S. patent application Ser. No. 13/046,648 filed Mar. 11, 2011, entitled "OPTICAL FIBER SENSORS HAVING LONG ACTIVE LENGTHS, SYSTEMS, AND METHODS", all of which is hereby incorporated by reference herein in its entirety for all purposes.

FIELD OF THE INVENTION

The present invention relates to optical sensors, and more particularly to optical fiber sensors and systems including them.

BACKGROUND OF THE INVENTION

Optical fiber strain sensors have been the topic of intense research during the last decade as they can be made very small, compact, immune to electromagnetic interference, biocompatible, and can be used at elevated temperature or in relatively harsh chemical environments. Applications for such sensors are, therefore, numerous and may range from structural monitoring to biomedical applications.

Certain fiber optic strain sensors are known in the art. One presented solution includes a specially designed double core fiber. Optical power is exchanged between the two cores as a function of applied strain. However, considerable lengths of optical fiber and complex signal processing may be required to make such systems practical. Other solutions are based on bend loss phenomena in the optical fiber where the applied strain modulates the intensity at a sensor output. For those solutions a relatively simple detection scheme may be applied, but they may have drawbacks in terms of relatively low sensitivity, relatively large size, and relatively low absolute accuracy that is typical for intensity-based sensors based upon bend loss phenomena.

Currently many fiber optic strain sensors are based on fiber Bragg gratings. Bragg grating sensors may however suffer from relatively high temperature sensitivity, require complex signal processing, and may not be miniature in their size (e.g., length). Other solutions to the optical fiber strain sensors rely on polarization effects in optical fibers and measurements of light pulse propagation time in a fiber that is exposed to a measured stress.

Certain strain sensing solutions can be obtained in the form of fiber-based Fabry-Perot sensors. Such fiber-based Fabry-Perot sensors may be appropriate for practical sensing applications since they may be interrogated by variety of straightforward and cost effective, commercially available optoelectronic interrogation techniques. In some applications, a Fabry-Perot interferometer may be used for strain measurements. For example, in the prior art, two perpendicularly cleaved optical fibers may be placed in a glass capillary in such a way to form the short air cavity between the fiber ends. This cavity creates an optical Fabry-Perot resonator that changes its length proportionally to expansion of the glass capillary. One drawback of this approach is in the use of adhesive and not well-defined point where fiber adheres to the capillary as the adhesive randomly penetrates the gap between fiber and capillary. Furthermore, the adhesion between capillary and fiber may impose thermal, mechanical, and chemical stability limitations. The outer diameter of such sensor is always considerably larger than the fiber diameter, which increases its size and may limit its possible applications and packaging options. Friction between the fiber and the capillary may cause sensor hysteresis. Furthermore, the production process of such capillary sensors may be complex and may involve number of precision alignment steps.

In another prior system, a hollow core optical fiber is used to create a spacer between two perpendicularly cleaved fibers. In this case, the sensor (hollow core optical fiber) has the same diameter as optical fibers but it relies on manufacturing and splicing of the hollow core optical fiber to a standard optical fiber which presents its own difficulties. In other embodiments, solutions including a concave cavity are used instead of hollow core fiber or capillary. In some embodiments, the creation of a strain sensitive cavity may be provided by an etching process. While such prior art optical sensors may eliminate some of the drawbacks of capillary-type sensors, they may suffer from limited sensitivity.

In prior art all-fiber designs, the cavity length is varied and converted into cavity length change under influence of an applied strain. The sensor sensitivity to the strain can be incensed by increasing the cavity length. However, this may lead to high optical losses, low interference fringe visibility and overall sensor signal degradation. In one solution, an air cavity is replaced by a fiber that can guide the light. For example, a section of single mode fiber is inserted between two semi-refractive mirrors to create a Fabry-Perot interferometer. While such solution allows for arbitrary resonator length, it may suffer from high temperature sensitivity induced by fiber core refractive index temperature dependence and may require a complex manufacturing procedure that involves vacuum deposition of mirrors onto the individual fiber surfaces. Furthermore, long Fabry-Perot cavities may require more complex signal processing techniques as the free spectral range of long cavity becomes narrow, requiring higher resolution spectrometric sensor signal interrogation techniques.

Furthermore, many, if not all, fiber Fabry-Perot strain sensors known in the art are made by complex and expensive production procedures that involve multiple production steps, and that are therefore not generally suitable for high volume, cost-effective production.

Thus, it should be recognized that the performance of such optical sensor devices may be limited, and/or manufacturing of such optical sensor devices may be relatively complicated and not cost effective. Therefore, there is a long felt and unmet need for highly effective optical sensor and manufacturing methods thereof.

SUMMARY OF THE INVENTION

In one aspect, an optical fiber sensor is provided. The optical fiber sensor includes a lead-in optical fiber having an end surface at a forward end; a first optical element having a body with an outer dimension, Do, a front end surface coupled to the lead-in optical fiber, a pedestal including a retracted surface that is spaced from the front end surface, the retracted surface at least partially defining an optical cavity, a gutter surrounding the pedestal, the gutter having a gutter depth defining an active region of length, L, the first optical element further exhibiting $L/Do \geq 0.5$.

In another aspect, a strain measurement system is provided. The system includes an optical fiber sensor adapted to be coupleable to an object undergoing strain, the optical fiber sensor including a lead-in optical fiber and an optical element coupled thereto, the optical element having an outer dimension, Do, and a pedestal including a retracted surface, the

retracted surface at least partially defining an optical cavity, a gutter surrounding the pedestal, the gutter having a gutter depth defining an active region of length, L, the first optical element further exhibiting L/Do≥0.5; and a signal processor coupled to the optical fiber sensor, the signal processor operable to generate and pass a light signal into the lead-in optical fiber, receive a light signal reflected from at least the retracted surface of the optical element, and determine a strain applied to the object.

In a method aspect, a method of manufacturing an optical fiber sensor is provided. The method includes providing a structure-forming fiber; and micromachining the structure-forming fiber to produce an outer dimension Do, a pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L, wherein L/Do≥0.5.

In a method aspect, a method of manufacturing an optical fiber sensor is provided. The method includes providing a structure-forming fiber having a central portion etchable at a first rate when exposed to an etching medium, a inner cladding portion surrounding the central portion having a second etching rate that is greater than the etching rate of the central portion when exposed to the etching medium, and an annular outer cladding portion surrounding the inner cladding portion having a third etching rate that is less than the etching rate of both the central portion and the inner cladding portion when exposed to the etching medium; and exposing an end of the structure-forming fiber to the etching medium for a sufficient time to produce an outer dimension Do, a pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L, wherein L/Do≥0.5.

In another method aspect, a method of manufacturing an optical fiber sensor is provided. The method includes providing a structure-forming fiber having a central portion having a composition of doped silica, an annular inner cladding portion surrounding the central portion having a composition of doped silica that is preferentially doped to provide an etching rate in an etching medium greater than the central portion, and an outer annulus portion surrounding the gutter portion and having a composition of substantially pure silica to provide an etching rate in the etching medium less than both the central portion and the annular inner cladding portion; and exposing an end of the first optical fiber segment to an etchant for a sufficient time to produce an outer dimension Do, pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L, wherein L/Do≥0.5.

In yet another method aspect, a method of using an optical fiber sensor is provided. The method includes providing an optical fiber sensor having a lead-in optical fiber having an end surface at a forward end, and a first optical element having a body with an outer dimension, Do, a front end surface coupled to the lead-in optical fiber, a pedestal including a retracted surface that is spaced from the front end surface, the retracted surface at least partially defining an optical cavity, a gutter surrounding the pedestal, the gutter having a gutter depth defining an active region of length, L, the first optical element further exhibiting L/Do≥0.5; coupling at least a portion of the body of the first optical element to an object undergoing strain; passing a light signal into the lead-in optical fiber from a signal processor, the signal processor operable to receive a reflected light signal from at least the retracted surface of the first optical element and determine a strain applied to the object.

In yet another method aspect, a method of using an optical fiber sensor is provided. The method includes providing an optical fiber sensor having a lead-in optical fiber having an end surface at a forward end, and a first optical element having a body with an outer dimension, Do, a front end surface coupled to the lead-in optical fiber, a pedestal including a retracted surface that is spaced from the front end surface, the retracted surface at least partially defining an optical cavity, a gutter surrounding the pedestal, the gutter having a gutter depth defining an active region of length, L, the first optical element further exhibiting L/Do≥0.5; providing at least a portion of the body of the first optical element in a space undergoing pressure changes; passing a light signal into the lead-in optical fiber from a signal processor, the signal processor operable to: receiving a light signal reflected from at least the retracted surface of the first optical element, and determine a pressure applied based upon length changes in the active region of the first optical element.

Numerous other aspects are provided in accordance with these and other aspects of the invention. Other features and aspects of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings. The drawings are not necessarily drawn to scale.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a cross-sectioned side view of an optical fiber sensor having an optical element according to embodiments of the invention.

FIG. **1**B is an end view of the optical element of the optical fiber sensor of FIG. **1**A according to embodiments of the invention.

FIG. **1**C is a cross-sectioned side view of the optical element of the optical fiber sensor of FIG. **1**A according to embodiments of the invention.

FIG. **2** is a cross-sectioned side view of a strain measurement system including the optical fiber sensor of FIG. **1**A coupled to an object undergoing strain according to embodiments of the present invention.

FIG. **3** is a cross-sectioned side view of another embodiment of an optical fiber sensor according to an aspect of the invention.

FIG. **4** is a cross-sectioned side view of yet another embodiment of an optical fiber sensor including multiple opposed optical elements according to an aspect of the invention.

FIG. **5** is a cross-sectioned side view of another embodiment of an optical fiber sensor including an optical element and a gutter thereof formed in a lead-in fiber according to an aspect of the invention.

FIG. **6** is a cross-sectioned side view of another embodiment of an optical fiber sensor wherein the optical element has a relatively larger outer dimension than a lead-in optical fiber.

FIG. **7** is cross-sectioned side view of another embodiment of an optical fiber sensor wherein the optical element has a relatively smaller outer dimension than a lead-in optical fiber.

FIG. **8**A is a measured change of the cavity length (nm) when the optical fiber sensor according to the present invention is exposed to strain (μm/m).

FIG. **8**B is a measured change of the cavity length (nm) when the optical fiber sensor according to the present invention is exposed to pressure (bar).

FIG. **9**A is a cross-sectioned side view of a structure-forming fiber used to manufacture the optical element according to an aspect of the invention.

FIG. **9**B is a cross-sectioned side view of the structure-forming fiber of FIG. **9**A used to manufacture the optical element taken along section line **9**B-**9**B.

FIG. **9**C is a respective cross-sectioned end view of an alternative structure-forming fiber used to manufacture the optical element according to an aspect of the invention.

FIG. **10** illustrates a cross-sectioned side view of an apparatus adapted to expose a structure-forming fiber to an etching medium to form the optical element according to an aspect of the invention.

FIG. **11** illustrates a cross-sectioned side view of an optical element according to an aspect of the invention.

FIG. **12** illustrates a cross-sectioned side view of an optical element bonded to a lead-in optical fiber according to an aspect of the invention.

FIG. **13** illustrates a cross-sectioned side view of an optical fiber sensor being trimmed to a desired total length (Lt) according to an aspect of the invention.

FIG. **14** illustrates a cross-sectioned side view of an assembly of a lead-in optical fiber bonded to a structure-forming fiber according to an aspect of the invention.

FIG. **15** illustrates a cross-sectioned side view of a structure-forming fiber of the assembly of FIG. **14** being trimmed to a desired total length according to an aspect of the invention.

FIG. **16** illustrates a cross-sectioned side view of an assembly after exposure to an etchant medium to form an optical element according to another aspect of the invention.

FIG. **17** illustrates a cross-sectioned side view of an assembly after bonding together of two assemblies shown in FIG. **16**.

FIG. **18** illustrates a cross-sectioned side view of an optical fiber sensor after trimming to a desired total length (Lt).

FIG. **19** illustrates a flowchart of a method according to the present invention.

FIG. **20** illustrates a cross-sectioned side view of an optical fiber sensor including a spacer of length (d) according to an aspect of the present invention.

FIG. **21** illustrates an end view of a structure-forming fiber according to an aspect of the present invention.

FIG. **22** illustrates a cross-sectioned side view of an optical fiber sensor in a pressure chamber according to an aspect of the present invention.

DETAILED DESCRIPTION

According to a first aspect, the present invention is an optical fiber sensor (e.g., a Fabry-Perot sensor) adapted for strain measurement and/or measurement of parameters that may be related to strain or elongation of an object. In other embodiments, the optical fiber sensor may be used as a pressure sensor and adapted to measure static and/or dynamically changing pressures. The optical fiber sensor of the present invention allows for separate control over a length (L) of an active region of the optical fiber sensor and over a length (d) of an optical cavity thereof. Accordingly, the present invention allows for design of high sensitivity sensors while also enabling the maintenance of a short optical cavity thereby permitting simple and economical signal interrogation. Furthermore, the optical fiber sensor may utilize a cavity (including a gas or vacuum) and the sensor body may be made entirely from silica and/or or doped silica. Utilizing a gas or vacuum cavity and silica and/or doped silica for the body may provide relatively low temperature sensitivity of the optical fiber sensor.

Accordingly, the present invention provides a relatively low temperature sensitivity, robust, fiber or nearly fiber size optical Fabry-Perot sensor (e.g., a strain or pressure sensor). The optical fiber sensor may have a length (L) of the active region which is relatively large, with arbitrary short cavity length (d) that enables attaining high strain sensitivity, high quality of output signal, and spectral characteristics that may be relatively easy to process.

A manufacturing method for the production of the optical fiber sensor is also disclosed. The method, in some embodiments, includes only one micromachining (e.g., etching step) and one bonding step. The micromachining step may be performed in large batches, which makes the optical fiber sensor of the present invention suitable for high volume, low cost manufacturing.

According to an aspect of the present invention, an optical fiber sensor is provided that is adapted to sense a parameter (e.g., strain) or parameters related to strain. The optical fiber sensor includes a lead-in optical fiber having a forward end. A first optical element (e.g., a single-piece optical element) is provided having a front end coupled to (e.g., bonded) the forward end of the lead-in optical fiber. The first optical element includes an outer dimension, Do, a pedestal with a retracted surface at least partially defining an optical cavity, a gutter surrounding the pedestal, the gutter having a gutter depth defining an active region of length, L, wherein the first optical element further exhibits $L/Do \geq 0.5$. The relatively long sensor active length (L) provides improved strain sensitivity.

In operation, the optical element is flexible in extension and/or compression in response to the parameter (e.g., strain or pressure), and the end surface of the lead-in optical fiber and the forward end of the retracted surface, respectively, define a rearward and a forward reflectors of a sensing Fabry-Perot resonator within the optical fiber sensor of the invention.

Optical fiber sensors in accordance with the embodiments described herein may be sensitive to several different parameters, e.g. strain, mechanical stress, force, pressure, length change, acceleration, vibration, chemical parameters, or combinations thereof that can directly or indirectly cause elongation or compression (e.g., strain or change in length) of the sensor's active length (L). The present invention can be particularly useful for applications where reduced size, immunity to electromagnetic interference (EMI), high thermal stability, and/or low drift are important characteristics.

These and other embodiments of the present invention are further described with reference to FIGS. **1**A-**22** below.

A first embodiment of the present invention optical fiber sensor **100** is described with reference to FIGS. **1**A-**1**C. The optical fiber sensor **100** of the present invention functions to sense a given parameter, as described herein. The parameter may be physical or chemical parameter. The optical fiber sensor **100** may include a lead-in optical fiber **102** having an end surface **103** at its forward end **104**. The end surface **103** may be cleaved to be generally perpendicular to an axial axis of the lead-in fiber **102** extending along the length dimension of the lead-in fiber **102**. The lead-in optical fiber **102** may include a core **105** and a cladding **106** and thus may possess a waveguide structure. The core **105** may be cylindrical and a cladding **106** may surround the core **105**, for example. The lead-in optical fiber **102** may function to guide a light signal(s) towards its end surface **103**, and then also guide a reflected light signal back in an opposite direction. It will be clear to one skilled in the art that the designation of lead-in optical fiber refers to the use of this fiber as a waveguide for the carrying a light signal and is not meant as representative of any particular property or structure of the optical fiber itself. The lead-in optical fiber **102** may be single mode optical fiber, multimode optical fiber. Other types of suitable optical fibers may be used. In some embodiments, the core **105** may be doped silica (e.g., germania-doped silica) and the cladding

106 may be substantially pure silica, for example. In other embodiments, the core 105 may be substantially pure silica and the cladding may be doped silica (e.g., fluorine-doped silica).

The optical fiber sensor 100 further includes an optical element 107, which may be a single-piece optical element, coupled to, and projecting forward from, the lead-in optical fiber 102. The optical element 107, shown in FIG. 1C, has a first end 110, which may be coupled (e.g. directly or indirectly) to the forward end 104 of the lead-in optical fiber 102, and a second end 111 opposite the first end 110. As will be described further herein, coupling between the lead-in fiber 102 and the optical element 107 may be by fusion/fusing via fusion splicing, for example. The first end 110 therefore faces rearwards of the optical element 107 while the second end 111 faces forwards. The designations of "rearward" and "forward" are used throughout the present specification to refer to the orientation of components with respect to light coming in from the lead-in optical fiber 102, and are not indicative of any preferential direction.

By "coupled" it is meant that the optical element 107 is directly connected or interconnected to the lead-in optical fiber 102. In some embodiments, the coupling between the lead-in optical fiber 102 and the optical element 107 may result from the optical fiber 102 and the optical element 107 being directly bonded together, for example. However, the optical element 107 and the end surface 103 of the lead-in optical fiber 102 need not necessarily be in direct contact, and the coupling may be by way of an intermediary component being provided. For example, an additional spacer 312 (see FIG. 3) may be present between the lead-in fiber 102 and the optical element 107 without departing from the scope of the present invention. For example, in more detail, the FIG. 3 embodiment includes an optical fiber sensor 300 having a lead-in optical fiber 102, an optical element 107, and a spacer 312. For example, the spacer 312 may be constructed of germania-doped silica forming the core 312A and a substantially-pure silica material forming the cladding, and may serve to modify, for example focus or collimate, the flied in the lead-in fiber 102. In other embodiments, a graded index cores may be used to provide focusing and collimation. Other spacer materials may be used.

When uninstalled, the optical element 107 is supported in a cantilevered fashion by the lead-in optical fiber 102, that is, no additional component is provided to support the optical element 107 such as would for example be the case for "capillary" type sensors where a base layer supports sensor components and receives the lead-in optical fiber in a channel therein.

In preferred installation configuration, the optical fiber sensor 100 of the invention may be part of a measurement system 200 that is adapted to measure a parameter of an object 202. For example, the optical fiber sensor 100 may be mounted to the object 202 undergoing strain as is shown in FIG. 2. The optical fiber sensor 100 may include a limited section (e.g., from less than a meter to several meters or more in length) of lead-in optical fiber 102. The optical element 107 and possibly part of the lead-in optical fiber 102 may be attached, for example glued or otherwise adhered to a surface 204 of the object 202 that is to be monitored for stress and/or elongation. A layer of adhesive 206, such as an epoxy resin, cyanoacrylate, or other suitable adhesive may be used to adhere or bond the optical fiber sensor 100 to the surface 204 of the object 202. As should be apparent, bending, flexion, vibration, etc. of the object 202 about its neutral axis 208 (shown dotted) will cause localized strain at the surface 204 that may be measured by the optical fiber sensor 100 and measurement system 200. An opto-electronic signal processor 210 may be coupled to the optical fiber sensor 100 and is adapted to send and receive light signals to and from the lead-in fiber 102. Any suitable opto-electronic signal processor 210 known in the art may be used to interrogate the optical fiber sensor 100. The lead-in fiber 102 may attached directly to the opto-electronic signal processor 210 or may be connected to one or more additional segments of optical fiber that attach to the opto-electronic signal processor 210.

The optical element 107, shown in FIGS. 1B-1C, further includes an outer dimension Do (e.g., an outer diameter), a solid support base 115 on the forward end 111, a reflective surface 116, and a gutter 117. The reflective surface 116 may be a semi-reflective surface. Air-glass transition causes about 3.6% back reflection. Optionally, an additional optical coating (e.g., TiO_2 or ZrO_2, etc.) may be added/deposited to the reflective surface 116 surface before splicing to further increase reflectivity. The reflective surface 116 may project rearwards, and is retracted inwardly (e.g., spaced and offset) relative to the first end 110 of the optical element 107. The reflected light signal may include reflection from the end surface 103 and also from at least the retracted surface 116 of the optical fiber sensor 100. The gutter 117 penetrates forward into the solid support base 115 by a distance (L) and surrounds the reflective surface 116 and pedestal 120. The second end 111 may be flat, angle cleaved, or of an arbitrary shape. A total length (Lt) of the optical element 107 can be of any practical length including, for example, lengths between several hundreds of micrometers and lengths that exceed centimeter range and can be thus considered infinite. However, in some embodiments, the optical element 107 may have a tail portion 121 having a length that extends beyond the forward end of the gutter 117 by a distance greater than Do/2, or even Do, or even 5 times Do, or even 10 times Do or more. Other lengths of tail portion 121 may be used.

The reflective surface 116 and gutter 117 in some embodiments may be centered relative to a longitudinal axis 122 the optical element 107. In some embodiments, the optical element 107, reflective surface 116, and gutter 117 may be circular or nearly circular in cross-section. Other cross-sectional geometries may be used. An inner gutter wall 118 and outer gutter wall 119 of the gutter 117 may be parallel to each other in some embodiments, or tilted (e.g., tapered) relative to the longitudinal axis 122. In the depicted embodiment, the inner gutter wall 118 is tilted relative to the optical element longitudinal axis 122 to define a generally conical-shape to the pedestal 120. The pedestal 120 includes the generally planar reflective surface 116 on its terminal rearward facing end. Tapered inner gutter wall 118 and reflective surface 116 defines a frusto-cone shape to form to the pedestal 120 of the optical element 107. The frustoconical shape provides additional mechanical stability and resistance to vibrations and transversal accelerations in case of high sensitivity optical fiber sensors utilizing the relatively deeper gutter 117 of the invention.

The reflective properties of fiber end surface 103 and a retracted reflective surface 116 of the optical element 107 may simply come from the interface between two different media, or be improved by providing a suitable semi-reflective layer onto the appropriate surface. The reflective or semi-reflective layers may, for example, be embodied by a metallic coating, oxide coating, or semiconductor coating of appropriate thickness. Such coatings and other options for providing reflective or semi-reflective layers are well known to those skilled in the art.

The end surface 103 of the lead-in optical fiber 102, and the retracted (e.g., spaced) reflective surface 116 of the optical

element **107** define an optical cavity **108** in the optical fiber sensor **100**. The optical cavity **108** may be an air or gas containing cavity, a vacuum containing cavity, or low pressure air or gas containing cavity (e.g., sub-atmospheric pressure). The optical cavity length (d) is defined by the distance between reflective surface **116** and the end surface **103** of the lead-in optical fiber **102** or other component. The reflective end surface **116** of the optical element **107** and reflective end surface **103** of the lead-in optical fiber **102** may further define a Fabry-Perot resonator. The end surface **103** and surface **116** may be co-planar, for example. Suitable dimensions are discussed herein below.

The optical fiber sensor **100** is flexible in bending in response to the parameter to be analyzed (strain, vibration, etc.). The optical fiber sensor **100** is primarily sensitive to elongation, more precisely in this embodiment to an elongation of an active region **124** having a generally annular shape and having a length (L) defined by the distance between the first end **110** (e.g., at the forward end **103** of the lead-in optical fiber **102**) and a bottom **123** of the gutter **117**. In the present invention, the first optical element **107** has a body with an outer dimension, Do, and the gutter has a gutter depth defining the active region of length L. To achieve relatively enhanced strain sensitivity, the first optical element **107** exhibits L/Do≥0.5. In other embodiments, the first optical element **107** comprises L/Do≥1.0, L/Do≥1.5, L/Do≥2.0, or even L/Do≥3.0.

Since the external stress or deformation imposed on the optical fiber sensor **100** is not transferred to the pedestal **120** supporting the reflective surface **116**, the axial elongation of active region **124** corresponds to a length change of dimension (d) of the cavity **108**. This length change of dimension (d) may be optically measured and determined by the opto-electronic signal processor **210** as shown in FIG. **2**.

In accordance with an aspect of the invention, the optical sensor **100** exhibits relatively longer Length (L) of the active region **124**, while the optical cavity length (d) of the optical cavity **108** can be set to relatively short practical values by the adjustment of a retraction of the reflective surface **116**. As described below, the retraction distance (d) can be controlled by a method according to another aspect of the invention. Having a relatively short optical cavity length (d) and a relatively longer length (L) of the active region **124** is advantageous. This is particularly advantageous for making strain measurements, where a longer length (L) of the active region **124** leads to proportionally larger cavity length change (Δx) when the optical sensor **100** is exposed to mechanical strain, while a relatively small optical cavity length (d) may provide a relatively low level of optical loss due to beam expansion (spreading) within the optical cavity **108**.

A relationship between the optical cavity length change and strain can be estimated as:

$$\Delta x = \epsilon L \qquad \text{Equation (1)}$$

wherein

ϵ is strain imposed on the optical fiber sensor **100**,

Δx is a change in cavity length, and

L is the length of the active region **124**.

Since the change in cavity length Δx is parameter measured by an appropriate opto-electronic signal processor **210**, a longer length (L) of the active region **124** therefore leads to higher sensor strain sensitivity. The change in the cavity length Δx may, for example, be measured on the basis of interference of reflected light in the Fabry-Perot resonator, and an appropriate optical signal processing system **210** can deduce therefrom a variation in the measured parameter. The optical processing of the signal is adapted to the characteristics of the Fabry-Perot resonator. Sensing by a Fabry-Perot resonator and appropriate signal processing techniques are well known to those skilled in the art and need not to be described further here.

Other physical or chemical parameters that can be related to strain or elongation of the active region **124** may also be measured by presented invention. These parameters may for example be mechanical stress, pressure, force, acceleration, vibration, humidity, presence of liquids such as carbohydrates, as well as other chemical parameters or combinations thereof.

The provision of an optical element embodying the retracted reflective surface **116** surrounded by gutter **117** and active region **124** of relatively long length (L) are advantageous structural features of the present invention. According to some embodiment, the optical element **107** reduces a number of weak and particularly problematic bonding points of the prior art through incorporation of a monolithic design of the optical element **107**. This design may increase sensor measurement range through the ability to sustain exposure to higher values of strain, provide improved robustness, and possibly relatively longer term reliability. In addition, manufacture is considerably simplified as compared to prior art methods, as will be seen further below. This may lead to considerable lower manufacturing costs.

According to some exemplary embodiments, the length (L) of the active region **124** may be typically between about 40 μm and about 2000 μm long, between about 125 μm and about 700 μm long, or even between about 170 μm and about 500 μm long (most preferable range). The length (d) of the optical cavity **108** may typically range between about 2 μm and about 50 μm, or even between about 5 μm and about 20 μm. The total length (Lt) of the optical element **107** can be of any practical length, typically between about 100 μm to about 5000 μm, however in many cases it can be up to few meters or more. The typical outer dimension (Do) (e.g., diameter) of the optical element **107** may be between about 80 μm and about 1000 μm.

In some embodiments, the outer dimension (Do) equals to the outer diameter of lead-in fiber **102**. For example, typical dimensions of an exemplary optical element **107** may be an outer dimension (Do—diameter) corresponding to about 125 μm, the active region **124** having a length (L) between about 200 μm to 300 μm (about 1.6 to 2.4 times Do), a length (d) of the optical cavity **108** between about 5 μm to about 15 μm, and a total length (Lt) of the optical element **107** of about 325 μm or more. These dimensions are given by way of example and are in no way intended to limit the scope of the present invention.

The optical element **107** is preferably made of inorganic materials, such as combinations of pure silica glass, doped silica glass, composite glass or sapphire, however it could be also made from polymer material or other materials. In some embodiments, the optical element **107** may be manufactured from a length of structure-forming optical fiber. The physical or chemical properties of the material selected need not be homogenous throughout the optical element **107** and may differ along particular axes or in different portions, for example by the provision of a radial distribution of dopants therein.

In some embodiments, the optical element **107** includes a compositional structure wherein the composition of the optical element **107** varies radially. A central portion forming the pedestal **120** may have a cylindrical shape with a higher refractive index as compared to the cladding, as in case of conventional optical fiber core. An inner cladding region which forms the gutter **117** may be an annulus preferentially-

doped with a dopant that causes the inner cladding region to exhibit an increased etching rate as compared to the central portion forming the pedestal **120**. An outer cladding portion forming the active region **124** and portion of the tail **121** may include an annulus having substantially no dopant (substantially pure silica) so that the etching rate of the annular outer cladding portion is less than the inner cladding portion. The doping rate of the central portion forming the pedestal **120** should be such that the central portion forming the pedestal **120** etches at a rate that is greater than the outer cladding portion. In this manner, etching with an etching medium may provide an axially retracted or offset surface (e.g., reflective surface **116**). Etching rates, as discussed above are of course relative, but etching is accomplished by using the same etchant material for each at the same time and under the same conditions.

In one example, the central portion may be a cylinder of germania-doped silica, the inner cladding portion may be and annulus of P_2O_5 doped silica, and the outer cladding portion may be an annulus of substantially-pure (undoped) silica. In some embodiments, the central portion may be a cylinder of germania-doped silica including between about 1% and about 20% germania dopant in silica, the inner cladding portion may be and annulus of P_2O_5 doped silica including between about 3% and about 20% P_2O_5 dopant in silica, or even between 3% and about 35% P_2O_5 dopant in silica, and the outer cladding portion may be an annulus of substantially-pure (undoped) silica. Optionally, the central portion may include one or more dopants selected from the group of TiO_2, P_2O_5, GeO_2, or B_2O_3, for example. Other dopants or combinations of dopants may be used.

Other practical embodiments and variations are described below with reference to FIG. **4** and FIG. **5**. For example, to double a length (L) of the active region **409** of the optical fiber sensor **400**, and, thus, double the sensor strain sensitivity, two optical elements **407**A and **107** (as previously described) may be joined together in an opposed orientation, as depicted, such that the openings open towards each other. The reflective surfaces **416**, **116** of both optical elements **407**A, **107** thus form an optical cavity **408**. The guidance of light to and from the cavity **408** may be provided either by a refractive index contrast at the interface between the gutter **417** and the pedestal **420** supporting the reflective surface **416** or by building a waveguide structure within the optical element **407**A. The waveguide structure may be achieved in the same way as described in FIG. **1**C or as otherwise described herein.

In the first alternative embodiment, shown in FIG. **4**, the optical element **407**A may be bonded (e.g., fusion spliced) to the lead-in fiber **102** and a distance between a bottom of the gutter **417** and the end face of the lead-in fiber **102** may be made as short as practical to minimize optical losses between the lead-in fiber **102** and the pedestal **420** supporting the reflective surface **416**. The elements **407**A and **107** may be bonded (e.g., fused) together at their respective annular portions. Optical element **407**A may be identical as optical element **107** described herein with reference to FIG. **1**A-**1**C.

In another alternative embodiment, an optical fiber sensor **500** is shown in FIG. **5**. The optical element **507** includes an optical element **107** as heretofore described coupled to an optical element **507** that is integral with the lead-in fiber **502**. In the depicted embodiment, a waveguide structure including a core **505**, an inner cladding **506**A and an outer cladding **506**B is provided. The core **505** may have a cylindrical shape with a higher refractive index as compared to the cladding **506**A, as in case of conventional optical fiber core. The inner cladding **506**A may be preferentially-doped with a dopant that causes the inner cladding to exhibit an accelerated etching rate as compared to the core **505**. The outer cladding **506**B may include a slight dopant or no dopant so that the etching rate of the outer cladding is less than the inner cladding **506**A. The doping rate of the core **505** should be such that the core **505** etches at a rate that is greater than the outer cladding **406**B. For example, the core **505** may be germania-doped silica, the inner cladding **506**A may be P_2O_5 doped silica, and the outer cladding **506**B may be substantially-pure (undoped) silica in the amounts as discussed above. The material composition of the lead-in optical fiber **502** and the optical element **107** may be substantially identical. Likewise, the outer diameter D_L of the lead-in fiber **502** and the outer dimension Do of the optical element **107** may be substantially the same.

In the depicted embodiment, the lead-in optical fiber **502** having the optical element **507**A etched into an end thereof may be coupled (e.g., via fusion splicing) to the optical element **107**. The waveguide structure of the lead-in optical fiber **502** can support one or more modes, and may be compatible in terms of dimensions of the core and refractive index difference with commercially available optical fibers, which can assure simple and low optical loss interconnectivity with standard optical fibers.

In the embodiments of FIG. **1**A through FIG. **5**, the optical elements **107** each have an outer dimension Do that is substantially equal to the outer diameter D_L of the lead-in optical fiber **102**, **502**. However, in some embodiments, the optical element may have a greater or smaller dimension than the lead-in optical fiber.

For example, FIG. **6** illustrates an embodiment of the optical fiber sensor **600** including an optical element **607** that has a larger outer dimension Do than an outer dimension D_L of the lead-in optical fiber **102**. An embodiment with a larger dimension optical element **607** may be advantageous for some applications, especially those requiring a higher sensitivity of the optical fiber sensor **600**, and where the miniature aspect of the optical fiber sensor is less of a concern. The larger dimension optical element **607** may, in general, allow for producing a relatively deeper gutter **617**, and, thus, the optical fiber sensor **600** may exhibit a relatively higher sensitivity to applied strain due to a relatively longer length (L) of the active region **624** being provided. The optical element **607** may have the same composition as discussed above for optical element **107** and may exhibit the same relationship between Do and L, i.e., $Do/L \geq 0.5$.

In some embodiments, the diameter of the optical element **707** may be smaller than that of the lead-in fiber **102**, such as in FIG. **7**, although such an embodiment may not provide additional advantage other than having a smaller dimension at the sensing tip.

FIG. **8**A demonstrates a typical experimentally-measured optical fiber sensor response for an exemplary optical fiber sensor according to embodiment shown in FIGS. **1**A-**2**. An optical fiber sensor **100** with diameter of 125 μm was glued onto a surface **204** of an object **202** (e.g., a flat steel plate) using an adhesive **206** (e.g., cyanoacrylate glue). The steel plate object **202** was then stressed to different predetermined values by application of an increasing amount of force to a portion of the object **202**. The applied stress resulted in progressively increasing strain (in μm/m) on the surface **204** of the object **202**. The plot of FIG. **8**A illustrates the change in cavity length (nm) of the optical fiber sensor **100** as a function of applied strain in μm/m when referenced forces are applied. The length (L) of the active region **124** of the optical fiber sensor **100** was about 250 μm with optical cavity length (d) of about 7 μm. The total length (Lt) of the optical element **107** was 278 μm. The adhesive **206** covered an area that was considerably longer than active region **124**.

In accordance with another aspect of the invention, there are also provided several variants of a method for manufacturing an optical fiber sensors (e.g., **107**) described above. The methods presented below are directed at manufacturing of an optical fiber sensor of the invention made from inorganic optical material such as pure or doped silica glass or sapphire.

Referring now to FIG. **9**A through FIG. **13** and FIG. **19**, illustrated are steps of a method according to first embodiment of the invention. According to the method **1900**, a structure-forming fiber (e.g., **900** as shown in FIG. **9**A-**9**B) is provided in **1902** having a suitable material composition. The material composition of the structure-forming fiber **900** may be preferentially doped and dopant concentrations and types may vary radially. The structure-forming fiber **900** may include multiple radial segments. For example, the structure-forming fiber **900** may have a cylindrical central portion **902** of doped silica, an annular inner cladding portion **904** surrounding the central portion **902** having a composition of doped silica that is substantially more preferentially etched than the central portion **902**. The doping to achieve preferential etching ensures a relatively higher etching rate when exposed to a common etchant material under the same conditions. Other methods of providing relatively higher etching rate may be provided, such as providing void structures in the annular inner cladding portion **904** such as micro-capillaries or nano-capillaries, or combinations of micro-capillaries or nano-capillaries with differential doping as is explained in more detail below. The structure-forming fiber **900** may include an annular outer portion **906** surrounding the inner cladding portion **904** that is substantially less preferentially doped than both the inner cladding portion **904** and the central portion **902**. Accordingly, the annular outer portion **906** may etch at an etching rate less than the central portion **902** and inner cladding portion **904** when exposed to a common etchant material under the same conditions.

The use of the term structure-forming fiber is not meant to infer any particular length, diameter, or structure. For example, the fiber **900** may be a rod. In step **1904** (FIG. **19**), a first end **908** (FIG. **10**) of the structure-forming fiber **900** that may be cleaved perpendicularly, and is exposed to an etching material **1000** for a sufficient time to reshape the first end **908** and produce an optical element **1100** (See FIG. **11**). Typical etching times may be between about 5 minutes and about 15 minutes in 40% HF at 25 C, for example. These values are exemplary only and will depend strongly on the etchant material (e.g., HF) concentration and temperature.

As shown in FIG. **11**, the produced optical element **1100** has an outer dimension Do, a pedestal **120**, and a gutter **117** surrounding the pedestal **120** having a gutter depth defining an active region **124** of length, L, wherein L/Do≥0.5. Higher levels of preferential doping of the inner cladding portion **904** may achieve relatively longer lengths (L) of the active region **124**. Thus, L/Do≥1.0, L/Do≥1.5, L/Do≥2.0, or even L/Do≥3.0 may be achieved through using higher levels of preferential doping.

In another method step **1906** as shown in FIG. **12**, the optical element **1100** is bonded (e.g., fused) to an end surface **103** of a lead-in optical fiber **102**. The bonding is preferably performed by fusion splicing, however other methods of bonding may be also applied. As mentioned above, the lead-in optical fiber **102** carries a sensing light signal to and from the optical fiber sensor (e.g., **100**). In the depicted embodiment, the lead-in optical fiber **102** may include a core **105** and a cladding **106** wherein the core **105** has a relatively higher refractive index than the cladding **106**. The diameter of the core **105** may be approximately the same as a diameter of the pedestal **120** at the surface **116**.

In an optional step **1908** in the method of FIG. **19** as best illustrated in FIG. **13**, the optical element **1100** of the optical fiber sensor **1300** may be shortened to the desired length (Lt), the desired dimensions of which are described herein. This step **1908** may be carried out by variety of simple procedures such as for example cutting, cleaving, polishing, or even simple breaking off of the end **1330** of the optical element **1100**.

FIGS. **14** to **18** illustrate steps of a manufacturing method adapted to manufacture an alternative embodiment of an optical fiber sensor **400** as shown in FIG. **4** wherein a second optical element **407**A is coupled between the first optical element **107** and the lead-in optical fiber **102**. The first step, shown in FIG. **14**, involves bonding a structure-forming fiber **900** as heretofore described to a lead-in optical fiber **102**, also as previously described to form a spliced assembly **1400**. In the second step, shown in FIG. **15**, the structure-forming fiber **900** is trimmed to a desired length dimension (Lt) thereby removing end **1530**. In the third step, as shown in FIG. **16**, the structure-forming fiber **900** is reshaped by exposure to an etching medium as previously described to produce a spliced assembly **1602** including an optical element **1600**, which may be substantially identical to the optical element **1100** of FIG. **11**. In the fourth step, shown in FIG. **17**, the lead-in optical fiber **102** having been bonded to the optical element **1600** is now coupled via bonding to another assembly, such as assembly **1602** shown on the right side. The assembly **1602** may be identical to the assembly **1602**. The assembly **1700** may include an optical element **1600** to form a dual element assembly **1700**. In other embodiments, the right assembly **1602** may contain only etched structure-forming fiber as described in FIG. **4**. The bonding may be preferably performed by fusion splicing, however other methods of bonding can also be applied. In a last optional step, optional step shown in FIG. **18**, the dual assembly **1700** including opposed optical elements **1600** may be shortened to the desired total length (Lt). This step can be carried out by variety of simple procedures such as cutting, cleaving, polishing, or even simple breaking off the end **1830**, for example.

The embodiment of optical fiber sensor **500**, as shown in FIG. **5**, may be formed in a similar manner. The first step involves reshaping structure-forming fiber as heretofore described to form optical element **507**A on the end thereof. In the second step, ends of both optical elements **507**A and **107** are bonded together (e.g., by fusion splicing or other methods). In the last, optional step, one of the optical elements not used to guide the light to and from the optical fiber sensor **500** is shortened to a desired length. By providing the optical elements in an opening-facing-opening configuration, the length (L) of the active region may be made twice as long.

In order to improve the signal produced by the Fabry-Perot cavity of the optical fiber sensors described herein, semi-reflective coatings may optionally be applied on the respective surfaces forming the Fabry-Perot cavity (e.g., end surfaces **103**, reflective surfaces **116**, etc.) before bonding.

According to a further aspect, as shown in FIGS. **9**A through **11**, the structure-forming fiber (e.g., **900**) may be formed by etching with an etching material into an optical element (e.g., **1100**) that embodies a pedestal **120** having a reflective surface **116** that is retracted from an end **110** by a distance (d) and wherein the pedestal **120** is surrounded by a gutter **117**. In some embodiments, the structure-forming fiber **900** has at least three regions of appropriate dimensions as shown in FIGS. **9**A and **9**B. Each region etches at a different etching rate when exposed to common etching medium (e.g.,

a gas or liquid). For example, the etching medium may be HF, buffered HF (mixture of HF and NH_4F), mixture of isopropyl alcohol and HF, SF6 and similar. A preferably etching medium is HF and isopropyl alcohol. The annular outer cladding portion **906** etches at a relatively slower rate, the inner annular cladding portion **904** etches at a relatively higher rate, and the central portion **902** etches at an intermediate rate that is higher than the etching rate of the outer cladding portion **906**, however slower than the etching rate of annular inner cladding portion **904**.

The etching rate of individual portions **902**, **904**, **906** may be manipulated through different mechanisms. For example, in some embodiments, introduction of dopants into a base silica glass leads to change of the etching rate upon exposure to the etching medium. Accordingly, each of the portions may be differentially doped. For example, if a silica glass in the cylindrical central region **902** is doped with GeO_2 (e.g., about 30 mol % in silica), which is a relatively standard doping level in a telecommunication multimode fiber, an etching rate in HF increases by approximately ten times when compared to an etching rate of pure silica when also exposed to the same HF etchant medium. Lower GeO_2 concentrations may provide proportionally lower etching rates, which may allow for setting of a desired etching rate for the central portion **902** to achieve the desired retraction and length (d). The central portion **902** may have a diameter the same as or slightly larger (to account for any etching thereof) to the diameter of the core **105** of the lead-in fiber **102**. For example, the diameter may be about 50 μm if a 50 μm MMF is used as the lead-in fiber, or about 10 μm if a single mode fiber is used for the lead in-fiber. Other diameters may be used depending upon the optical design. An etching rate of the annular inner cladding region **904** is made relatively higher to achieve the long length (L) of the active region **124**, and, thus, relatively high sensitivity of the optical fiber sensor **1100** to the strain. A suitable dopant for the annular inner cladding region **904** that may increase the etching rate in HF at even moderate doping levels is P_2O_5 (e.g., concentrations of about 3 mol % to about 20%, or even about 3% to about 35 mol % in silica or more). The annular inner cladding region **904** may include a thickness of between about 1 μm to about 15 μm. Other dimensions may be used. However, making the annular inner cladding region **904** relatively thin is believed to maximize achievable depth of the gutter **117** as isotropic etching will causes axial/radial removal of material. The annular outer cladding region **906** may be substantially-pure silica. The outer dimension of the annular outer cladding region **906** may be approximately equal to the lead-in fiber **102**. The structure-forming fiber **900** may be drawn using conventional fiber drawing methods from a fiber preform or boule. The fiber preform may be manufactured by an outside vapor deposition (OVD) method, an inside vapor deposition (e.g., modified chemical vapor deposition—MCVD), rod-in-tube methods, stack-and-draw methods, or other suitable preform manufacturing methods known to those of skill in the art.

In embodiments where differential doping is used to manipulate the etching rate in the etching medium and thereby reshape the structure-forming fiber **900** into an optical element (e.g., **1100**), it may be advantageous in some embodiments to introduce an additional barrier region **909** into the structure-forming optical fiber (see FIG. **9**C). This barrier region **909** may be provided between the central portion **902** and first cladding portion **904** and should etch at a relatively slower etching rate (e.g. at the same rate as the outer cladding portion **906**). The purpose of the barrier region **909** is to reduce a transverse (radial) etching rate of the central portion **902** that would otherwise be etched at a moderate etching rate. This aids in achieving a long length (L) of the active region **124**. The introduction of the barrier region **909** may therefore reduce an angle (e.g., taper) of the gutter inner walls (See **118**, **119** of FIG. **1**A), and, thus, allows for longer etching time that leads to longer gutter and higher final sensor sensitivity. The barrier region **909** therefore acts as a barrier that protects central portion **902** from excessive radial (e.g., side) etching. Additional differentially doped layers may be added.

The barrier region **909** may be made of substantially pure silica to achieve a relatively low etching rate in the etchant medium (e.g., HF). Radial thickness of the barrier region **909** may be between about 5 μm and about 50 μm. Other thicknesses may be used. It should be recognized that the provision of a barrier region **909** may also provide a relatively low refractive index of the barrier region **909** when compared to the refractive index of central portion **902** that may be doped with an index-raising dopant (e.g., germania), and, thus, may have a relatively higher refractive index than pure silica. This contrast in refractive index between the central portion **902** and the barrier region **909** creates a waveguide structure that may guide light along optical element **1100**.

Waveguide structure in the optical element **1100** may also be created by proper doping of the central portion **902**. A single dopant or combinations of dopants that significantly increase refractive index of the silica without significant influence on etching rate may be used. In some embodiments, TiO_2 may be used as a dopant for the central portion **902**. For example, about 2 mol % to about 7 mol % TiO_2 in silica may be used. In this case an appropriate index contrast may be achieved between central portion **902** and annular inner radial portion **904** being doped with about 3 mol % to about 20 mol % P_2O_5 in silica, or even about 3 mol % to about 35 mol % P_2O_5 in silica, or by the use of a substantially pure silica barrier region as described above.

Further refinement in control over waveguide structure cross section dimensions can be achieved by combination of two dopants in the central portion **902**. The use of two dopants may provide refractive index contrast within the central portion **902**, while at the same instance providing a uniform etching rate across the central portion **902**. More specifically, as shown in FIG. **21**, the central portion **902** may be split into two sub-regions **911**, **912**, e.g. to the inner sub-region **911** and an outer sub-region **912**. The inner sub-region **911** may be silica doped with TiO2 (e.g., 2.0 mol % or more in silica) that considerably increases refractive index, but only moderately increases the etching rate. The outer sub-region **912** may be silica doped with dopant or combination of dopants that increases the etching rate but induces limited change in refractive index (e.g. P_2O_5, less than 1 mol % in silica). Proper adjustment of dopant levels may lead to the creation of index contrast between the inner sub-region **911** and outer sub-region **912** while providing uniform etching of the entire central portion **902**. Such a configuration may create a waveguide structure of preferred diameter, while the entire central portion **902** etches into uniform and flat end surface and thus forms retracted reflective surface **116** of the optical element **1100**.

The etching rate of individual layers or portions in the structure-forming fiber may also be manipulated through mechanisms other than by differential doping, or by other methods in addition to differential doping. Creation of layers or portions that include small voids may be provided. For example, the void structures may be provided by including porosity or micrometer-size or nanometer-size capillaries in the structure-forming fiber. Such layers or portions including void structures may etch at considerably different rates due to

capillary action/force that draws the etching medium (e.g., acid) deep into capillaries, as compared to an etching rate in bulk glass layers (e.g., not including such porosity or capillaries). Introduction of micro-size or nano-size capillaries may be suitable for creation of the inner annular cladding portion **904** that forms the gutter **117** upon etching and that generally needs to etch at a highest relative rate. Capillaries may be formed by formation of fiber preform using stack and draw method wherein hollow tubes are arranged in a bundle and drawn, drilling of the fiber preform, by formation of porous layers in fiber production, or other known fiber production process typically used in photonic crystal production. The void structures may be provided in a sufficient amount to provide a density reduction of about 20% to 70% as compared to bulk glass, for example. Capillaries may have a mean diameter size of between about 0.01 μm and 20 μm, for example. Other dimensions may be used. Combinations of the above void structures with differential doping may also be used.

Exemplary designs of the optical element and structure-forming fibers thereof are described in Tables 1 and 2 below. These are exemplary only, and other suitable design variations may be used. Table 1 is directed at an embodiment including a barrier layer **909** formed around the central portion **902**. Table 2 is directed at a design having no barrier layer around the central portion **902**.

TABLE 1

Optical Element and Structure-Forming Fiber Designs

	Lead-in fiber properties	Case 1 50 μm core, 125 μm OD fiber	Case 2 10 μm core, 125 μm OD fiber	Case 3 50 μm core, 140 μm OD fiber	Case 4 10 μm core, 140 μm OD fiber	Case 5 50 μm core, 200 μm OD fiber	Case 6 10 μm core, 200 μm OD fiber
Exemplary Optical Element	Wall thickness (Tw) μm	5	5	7	7	7	7
	Optical cavity length (d) μm	5	5	5	5	5	5
	length (L) of active region (minimum) μm	280	550	350	600	750	1000
	Reflective surface (116) diameter μm	50	10	50	10	50	10
Structure-Forming Fiber	Inner cladding portion (904) thickness μm	10	10	10	10	10	10
	Central portion (902) diameter μm	50	10	50	10	50	10
	Barrier region (909) thickness μm	11	21	14	24	29	39
	Outer diameter μm	147.5	167.5	168	188	258	278
	Relatively higher etching rate of the central portion (902)	1.44	1.24	1.36	1.21	1.17	1.13
	Minimal relatively higher etching rate of the inner cladding portion (904)	30	30	30	30	30	30
Expected Performance	Final sensor active length L	326	616	406	696	841	1131
	L/Do (estimated L/Do ratio)	2.6	4.9	2.9	5.0	4.2	5.7

TABLE 2

Optical Element and Structure-Forming Fiber Designs

	Lead-in fiber properties	Case 7 50 um core, 125 um OD fiber	Case 8 10 um core, 125 um OD fiber	Case 9 50 um core, 140 um OD fiber	Case 10 10 um core, 140 um OD fiber	Case 11 50 um core, 200 um OD fiber	Case 12 10 um core, 200 um OD fiber
Exemplary Optical Element	Wall thickness (Tw) μm	5	5	7	7	7	7
	Optical cavity length (d) μm	5	5	5	5	5	5
	(Minimum) active region of length (L) μm	220	470	280	550	650	900
	Reflective surface (116) diameter μm	50	10	50	10	50	10

TABLE 2-continued

Optical Element and Structure-Forming Fiber Designs							
	Lead-in fiber properties	Case 7 50 um core, 125 um OD fiber	Case 8 10 um core, 125 um OD fiber	Case 9 50 um core, 140 um OD fiber	Case 10 10 um core, 140 um OD fiber	Case 11 50 um core, 200 um OD fiber	Case 12 10 um core, 200 um OD fiber
Structure-Forming Fiber	Inner cladding portion (904) thickness μm	10	10	10	10	10	10
	Central portion (902) diameter μm	67.5	47.5	73	53	103	83
	Structure-forming fiber outer diameter μm	143	163	163	183	253	273
	Relatively higher etching rate of the central portion (902) μm	1.6	1.3	1.4	1.2	1.2	1.1
	Minimal relatively higher etching rate of the inner cladding portion (904) μm	30	30	30	30	30	30
Expected Performance	Final sensor active length L μm	254	544	334	624	769	1059
	L/Do (estimated L/Do ratio)	2.0	4.4	2.4	4.5	3.8	5.3

The dimensions, doping levels and composition of regions that form structure-forming fiber may be varied depending upon the desired sensor system specifications and properties. Among the variables are:

a) lead-in fiber outer diameter (OD),

b) thickness of inner cladding portion (**904**),

c) desired optical cavity length (d),

d) active region length (L),

e) diameter of reflective surface **116**, and

f) minimum sensor wall thickness (Tw).

While the lead-in fiber outer diameter (OD) may be arbitrary, the standard dimension of 125 um, is often desired for practical reasons. Larger dimension of lead-in fibers might be also of interest due to the possibility to design sensors with larger optical element diameter and consequently larger active region length (L) that may result in higher sensor sensitivity. The active region length (L) is correlated with structure-forming fiber diameter mainly due to the isotropic etching process that removes some of the low etching rate material/regions in all exposed directions including radial direction, e.g. low etching rate region such as silica outer cladding will be also etched in radial direction from the inside (gutter side). Larger outer diameters of the structure-forming fiber thus allows for longer etching times and consequently deeper gutters.

The active region length (L) determines the sensor system's strain sensitivity. In most practical applications it should be chosen to be as long as possible. This dimension will be determined by relatively higher etching rate of the inner cladding portion **904** and available material/space around the inner cladding portion **904** as described in previously.

The optical cavity length (d) of the sensor is mainly determined by signal interrogation principle that is used in measurement system and can range from few micrometers up to about 50 μm or even more. In accordance with the present invention, the cavity length (d) can be thus chosen to fit most known signal integration systems.

The inner cladding portion (**904**) thickness, when present, may be made sufficiently thick to allow for exchange between etching by-products generated within the gutter during etching and bulk of the etching medium. Typically this thickness may be in the range of 3-15 μm.

The diameter of the reflective surface **116** is mainly governed by lead-in fiber core diameter. The lead-in fiber core diameter depends on signal processing technique and can be in generally single mode or multimode. In the later case, the core is typically 50 μm or more in diameter, while in the first case the core diameter is usually below 10 μm. In order to reflect back significant portion of the incoming light the reflective surface **116** may have dimensions substantially similar to lead-in fiber core diameter. Larger diameters of reflective surface **116** than of lead-in fiber core diameter are also possible, but are in generally less practical as they limit the size of the fiber cross sectional area that is available for radial etching of the area surrounding gutter **117** as explained above.

Minimum sensor wall thickness Tw is mainly determined by minimum acceptable tensile strength of the optical sensor system. The minimum optical sensor wall thickens that occurs at the bonding surface between lead-in fiber and optical element is a region of the sensor where the highest mechanical stress is concentrated. Depending on the strain range and dynamic load conditions, a certain minimum sensor wall thickness is required to provide desired sensor durability and desired life expectancy. Sensor wall thickness may be, for example, in the range between about 2 μm and 30 μm or even more, especially when large diameter optical elements are utilized.

As briefly described above, there are many design parameters that determine optical sensor and consequently structure-forming fiber design. A few examples of possible structure-forming fiber designs based on particular sets of input parameters (including various lead-in fiber parameters) are given in Tables 1 and 2 for both embodiments (the embodiments with and without barrier region **909**). In addition to the input parameters, the following additional conditions were used in the optical sensor of Table 1 and 2.

1) All optical elements have substantially a same outer diameter as the lead-in fiber.

2) The relatively higher etching rate of the inner cladding portion **904** in the etching medium is about 30 times higher than an etching rate of substantially pure silica.

3) The structure-forming fiber is etched from its initial diameter to the outer diameter corresponding to the lead-in fiber diameter.

The dimensions of structure-forming fibers and optical elements shown in Table 1 and 2 above are exemplary. Other dimensions are possible.

Another manipulation of the etching rate can be achieved by intense illumination of particular portion or layer (e.g., the gutter-forming portion **904**) with an ultraviolet light that creates microcracks in the illuminated glass. Such portions including microcracks may etch at considerably higher rate than normal uniform bulk glass. Detail description of this phenomenon is described in "Shape control of microchannels fabricated in fused silica by femtosecond laser irradiation and chemical etching," Opt. Express, volume 17, 8685-8695 (2009) by Vishnubhatla et al, the disclosure of which is hereby incorporated by reference herein.

As shown in FIG. **20**, a optical fiber sensor **2000** including optical element **2007** may also be produced by lithographic process that involves masking an end of the structure-forming fiber and then etching the gutter **2017** using a lithographic process or by a direct laser micromachining method. Micromachining using a pico-second or femto-second laser may be used. In such methods, creation of a gutter **2017** in the optical element **2007** may be provided. However a retraction of the reflective surface **2016** must be separately created. The length (d) of the optical cavity **2008** may be adjusted by bonding (e.g., fusion bonding) a short spacer **2050** of length (d) made from a silica glass tubular capillary in-between the lead-in fiber **102** and lithographically etched or micro-machined member. However, it should be recognized that a simple manufacturing method may be achieved by differential etching method as described herein.

In another installation configuration, the optical fiber sensor **100** of the invention may be part of a pressure measurement system **2200** that is adapted to measure a pressure of a space such as a chamber **2205**. For example, the optical fiber sensor **100** may be mounted to the walls **2206** of the chamber **2205** or otherwise included in or interconnected to the chamber **2205** undergoing a pressure change sought to be measured, as is shown in FIG. **22**. The optical fiber sensor **100** may include a limited section of lead-in optical fiber **102**. At least a portion of the body of the optical element **107** and possibly part of the lead-in optical fiber **102** may be received in the chamber **2205** undergoing a pressure change. Pressure exposure to the optical element **107** causes localized strain along the active region of the optical fiber sensor **100** that may be measured by the optical fiber sensor **100** and pressure measurement system **2200**.

An opto-electronic signal processor **2210** may be coupled to the optical fiber sensor **100** and is adapted to pass and receive light signals to and from the lead-in fiber **102**. The signal processor **2210** is operable to receive light signals reflected from at least the retracted surface of the optical element **107**, and determine a pressure applied to the optical fiber sensor **100** based upon length changes of the active region of the optical element **107**. Any suitable opto-electronic signal processor **2210** known in the art may be used to interrogate the optical fiber sensor **100**. The lead-in fiber **102** may attached directly to the opto-electronic signal processor **2210** or may be connected (e.g., spliced) to one or more additional segments of optical fiber that attach to the opto-electronic signal processor **2210**. The plot of FIG. **8**B illustrates typical change in cavity length (nm) of the optical fiber sensor **100** as a function of applied pressure in bar.

The foregoing description discloses only exemplary embodiments of the invention. Modifications of the above-disclosed apparatus, systems, and methods which fall within the scope of the invention will be readily apparent to those of ordinary skill in the art. Accordingly, while the present invention has been disclosed in connection with exemplary embodiments thereof, it should be understood that other embodiments may fall within the spirit and scope of the invention, as defined by the following claims.

The invention claimed is:

1. A method of manufacturing an optical fiber sensor, comprising:

providing a structure-forming fiber having a first end; and

micromachining the structure-forming fiber to produce an outer dimension Do measured at an outermost dimension of the optical fiber sensor, a pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L measured between the first end and a bottom of the gutter,

wherein L/Do≥0.5

wherein a material micromachined to form the gutter comprises P_2O_5-doped silica.

2. A method of manufacturing an optical fiber sensor according to claim **1**, wherein L/Do≥1.0.

3. A method of manufacturing an optical fiber sensor according to claim **1**, wherein L/Do≥1.5.

4. A method of manufacturing an optical fiber sensor according to claim **1**, wherein L/Do≥2.0.

5. A method of manufacturing the optical fiber sensor according to claim **1** further comprising forming a tail portion that extends beyond a forward end of the gutter by a distance greater than Do/2.

6. A method of manufacturing an optical fiber sensor according to claim **1** further comprising forming a tail portion that extends beyond a forward end of the gutter by a distance greater than Do.

7. A method of manufacturing an optical fiber sensor according to claim **1** further comprising forming a tail portion that extends beyond the forward end of the gutter by a distance greater than or equal to 5 Do.

8. A method of manufacturing an optical fiber sensor according to claim **1** wherein the gutter is formed from a material comprising micro-capillaries or nano-capillaries.

9. An optical fiber sensor formed by the process of claim **1**.

10. A method of manufacturing an optical fiber sensor, comprising:

providing a structure-forming fiber; and

micromachining the structure-forming fiber to produce an outer dimension Do, a pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L,

wherein L/Do≥0.5

wherein the structure-forming fiber includes:

P_2O_5-doped silica in an axial region adjacent to the gutter-forming region;

doped silica in the pedestal-forming region having a refractive index increasing dopant; and

substantially pure silica in an outer annulus of the structure-forming fiber.

11. A method of manufacturing an optical fiber sensor, comprising:

providing a structure-forming fiber having a central portion etchable at a first rate when exposed to an etching medium, an inner cladding portion surrounding the cen-

tral portion having an etching rate that is greater than the etching rate of the central portion when exposed to the etching medium, and an annular outer cladding portion surrounding the inner cladding portion having an etching rate that is less than the etching rate of both the central portion and the inner cladding portion when exposed to the etching medium; and

exposing an end of the structure-forming fiber to the etching medium for a sufficient time to produce an outer dimension Do, a pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L,

wherein L/Do≥0.5.

12. A method of manufacturing an optical fiber sensor according to claim **11**, wherein:

the central portion of the structure-forming fiber comprises doped silica having a refractive index increasing dopant;

the inner cladding portion comprises P_2O_5-doped silica;

the outer cladding comprises substantially pure silica.

13. A method of manufacturing an optical fiber sensor according to claim **11**, wherein the inner cladding portion comprises capillaries.

14. An optical fiber sensor formed by the process of claim **11**.

15. A method of manufacturing an optical fiber sensor, comprising:

providing a structure-forming fiber having a central portion having a composition of doped silica, an annular inner cladding portion surrounding the central portion having a composition of doped silica that is preferentially doped to provide an etching rate in an etching medium greater than the central portion, and an outer annulus portion surrounding the gutter portion and having a composition of substantially pure silica to provide an etching rate in the etching medium less than both the central portion and the annular inner cladding portion; and

exposing an end of the first optical fiber segment to an etchant for a sufficient time to produce an outer dimension Do, pedestal, and a gutter surrounding the pedestal having a gutter depth defining an active region of length, L, wherein L/Do≥0.5.

16. A method of manufacturing an optical fiber sensor according to claim **15**, wherein L/Do≥2.0.

17. A method of manufacturing an optical fiber sensor according to claim **15** further comprising forming a tail portion that extends beyond a forward end of the gutter by a distance greater than Do.

18. A method of manufacturing an optical fiber sensor according to claim **15**, wherein the annular inner cladding portion comprises capillaries.

19. An optical fiber sensor formed by the process of claim **15**.

* * * * *